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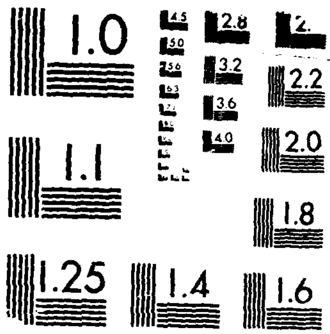

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In-House Report
March 1988

RAIN ATTENUATION AT 35 GHz OVER AN 18-KM PATH

Edward E. Altshuler

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In this paper an experiment to measure attenuation as a function of rain rate is described. The measurements were made at a frequency of 35 GHz over an 18.3-km path between Griffiss Air Force Base and Verona, NY. Four tipping-bucket rain gauges were located along the path. The beamwidths of the antennas were sufficiently narrow and the antennas were sufficiently high above the ground so as to preclude interference from any terrain effects. Rain rate and received signal level were measured at one-minute intervals; however, equipment malfunctions prevented data from being collected on a continual basis. In addition, it was found that the rain gauges did not operate reliably during snow and very cold weather so they were not used during the winter. Therefore, it was not possible to obtain percent time statistics for rain attenuation for upper New York State. However, 91.5 hours of data were collected during 10 rainstorms. A linear regression of attenuation as a function of rain rate was performed

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for each set of data. Based on the results that were obtained it appears that the rain attenuation has a fair amount of variability and that the measured attenuations are somewhat higher than those predicted by theory. A reason for this excess attenuation may be due to the fact that the rain gauges were spread too sparsely along the path and that heavier localized rain went undetected.

Preface

The author wishes to thank Mr. Joseph Parry for making arrangements to obtain the data and Sgt. Wade Warrens and Mr. Robert Walker for computer programming support.

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1. INTRODUCTION

In order to design a millimeter wave communication system it is necessary to have propagation statistics available. The principal propagation effects at millimeter wavelengths are produced by gaseous absorption due to oxygen and water vapor, terrain multipath, anomalous refractivity structure and precipitation. From a statistical standpoint, precipitation in general and rain in particular are the most serious limitations. Gaseous absorption can be estimated quite accurately and is relatively small at the longer millimeter wavelengths as compared to attenuation due to precipitation. Attenuation due to terrain multipath is a function of the path geometry and can be avoided by properly designing the link. Refractivity effects are very difficult to estimate; however, they are generally rare events for most locations and the likelihood of occurence diminishes as the link becomes shorter. Rain attenuation by far presents the most serious problem, so it is important that attenuation data be collected so that the needed statistics can be generated.

Rain is an extremely complex phenomenon, both meteorologically and electromagnetically. From a meteorological standpoint it is generally nonuniform in shape, size, orientation, temperature, and distribution, thus making it very difficult to model. Electromagnetically, the absorption, scattering, and depolarization characteristics can be calculated only for very simple shapes and distributions. However, theoretical results do provide a qualitative understanding of the effects of rain on millimeter waves, and when they are combined with experimental data, empirical parameters can be derived and more quantitative results are possible.

At the longer millimeter wavelengths the attenuation is primarily a function of the amount of rain along the path. The meteorological parameter which is most easily measured and which best characterizes the rain is the rain rate. Only a limited number of controlled experiments to measure

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attenuation as a function of rain rate have been conducted near a frequency of 35 GHz. Medhurst[1] has compared experimental results with theoretical values and concluded that there is a tendency for the measured values to exceed the maximum possible levels predicted by theory. Norbury and White[2] measured attenuation at 35.8 GHz over a 448-meter path over which there were 4 rain gauges. Their experimental results were in good agreement with theoretical values that were calculated using a Laws and Parsons[3] drop size distribution. Zavody and Harden[4] measured attenuation at 36 GHz over a 220-meter path with 4 equally-spaced rain gauges along the path and also obtained good agreement with theory. Mink[5], however, using a shuttle pulse technique and a propagation path of only a few meters obtained attenuations at 35 GHz that were higher than those predicted by theory. Thus, at this point in time, satisfactory agreement between theory and experiment has not been established. However, even if it is conceded that acceptable agreement can be obtained for a very short path, there is still the more practical case of longer paths to contend with. In this paper, a controlled experiment to measure attenuation as a function of rain rate is described. In Section II a brief discussion of theoretical considerations is presented. In Section III we describe the experimental setup. The procedure used to analyze the data is discussed in Section 4, and the conclusions are discussed in Section 5.

2. THEORETICAL CONSIDERATIONS

Let us first examine the absorption and scattering characteristics of a single spherical raindrop. We can calculate the total cross section Q_t, which is the sum of the absorption cross section Q_a and the scattering cross section Q_s. This cross section is a strong function of the drop diameter and its complex index of refraction. In Figure 1, the total cross section of a drop is plotted as a function of drop radius for several wavelengths. The scattering and absorption cross sections Q_s and Q_a are proportional to $(D/\lambda)^6$ and $(D/\lambda)^3$ respectively. When the drop is very small with respect to wavelength, the Rayleigh approximation is valid. Thus, the loss due to scattering is negligible compared to that due to absorption and the total cross section is proportional to the volume of the drop. As the drop becomes larger both the scattering and absorption cross sections continue to increase, with the scattering cross section increasing more rapidly. Finally, after reaching a peak, the

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1. Medhurst, R.G. (1965) Rainfall attenuation of centimeter waves: comparison of theory and experiment, *IEEE Trans. Antennas Propag.* **AP-26**(2), 318-329.
2. Norbury, J.R. and White, W.J.K. (1972) Microwave attenuation at 35.8 GHz due to rainfall, *Electron. Lett.* **8**, 91-91.
3. Laws, J.O. and Parsons, D.A. (1943) The relation of rain drop size to intensity, *Eos Trans. AGU* **24**, 452-460.
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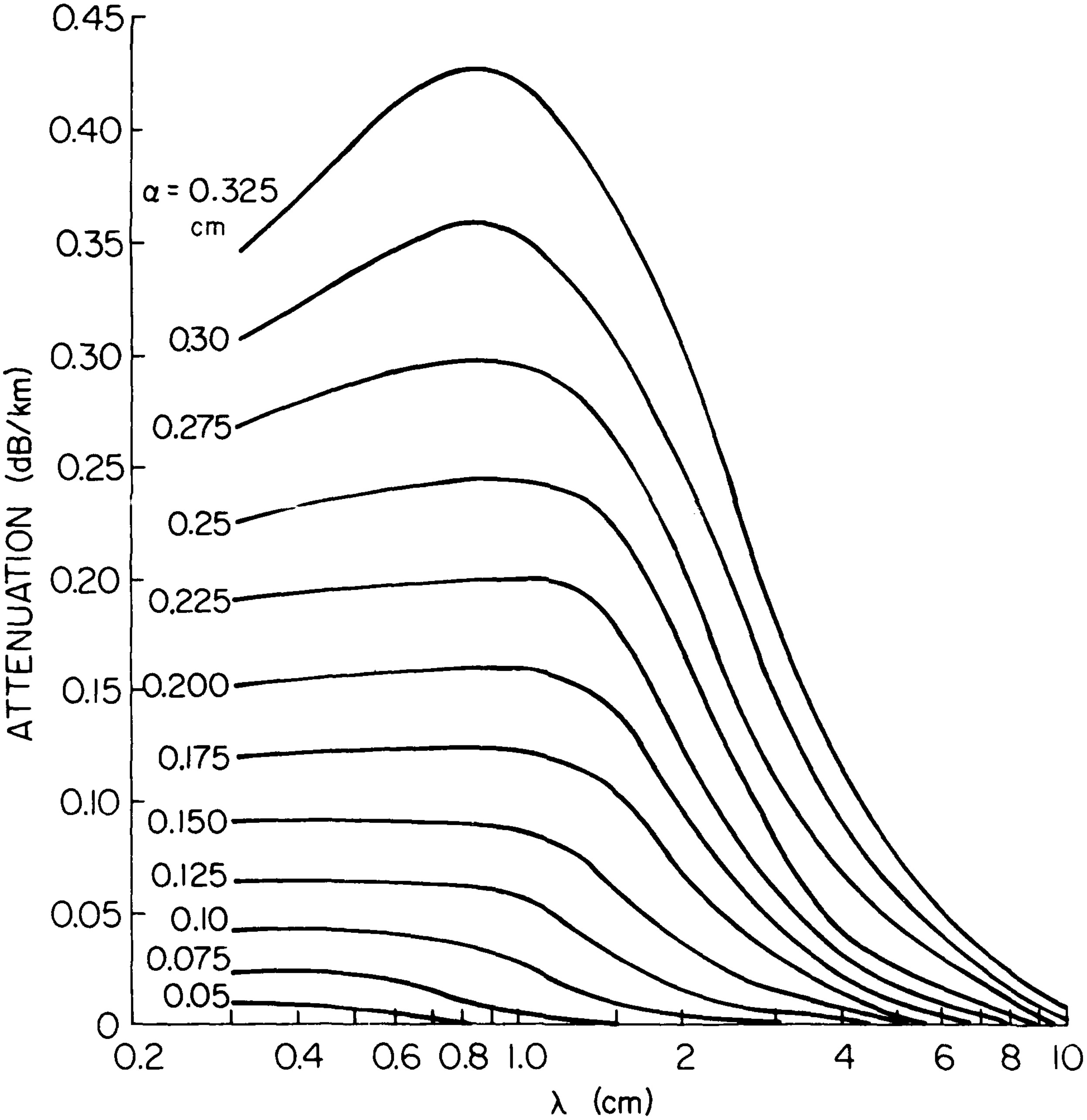

Figure 1. Theoretical Values of Attenuation by Raindrops for Various Drop Radii

total cross section begins to level off, and would eventually approach a value of twice the geometric cross section of the drop when it is very large with respect to wavelength. Thus, as the drop becomes larger, the cross section, which is initially proportional to the drop volume, becomes proportional to the drop area. Rain can be considered to consist of a collection of drops having diameters ranging from a fraction of a millimeter (mist) up to possibly 7 mm. To compute the attenuation of rain, the cross sections of the drops must be calculated and then summed. Because the characteristics of a precipitation system are controlled largely by the air flow, the net result is a collection of drops that is continually varying both spatially and temporally; thus, it is very difficult to model. The drop size distribution of rain is related to the rain rate. For most models, it is assumed that light rain consists mainly of very small drops. As the rain rate increases the number of larger drops increases as is shown in Figure 2, (Burrows and Atwood)[6].

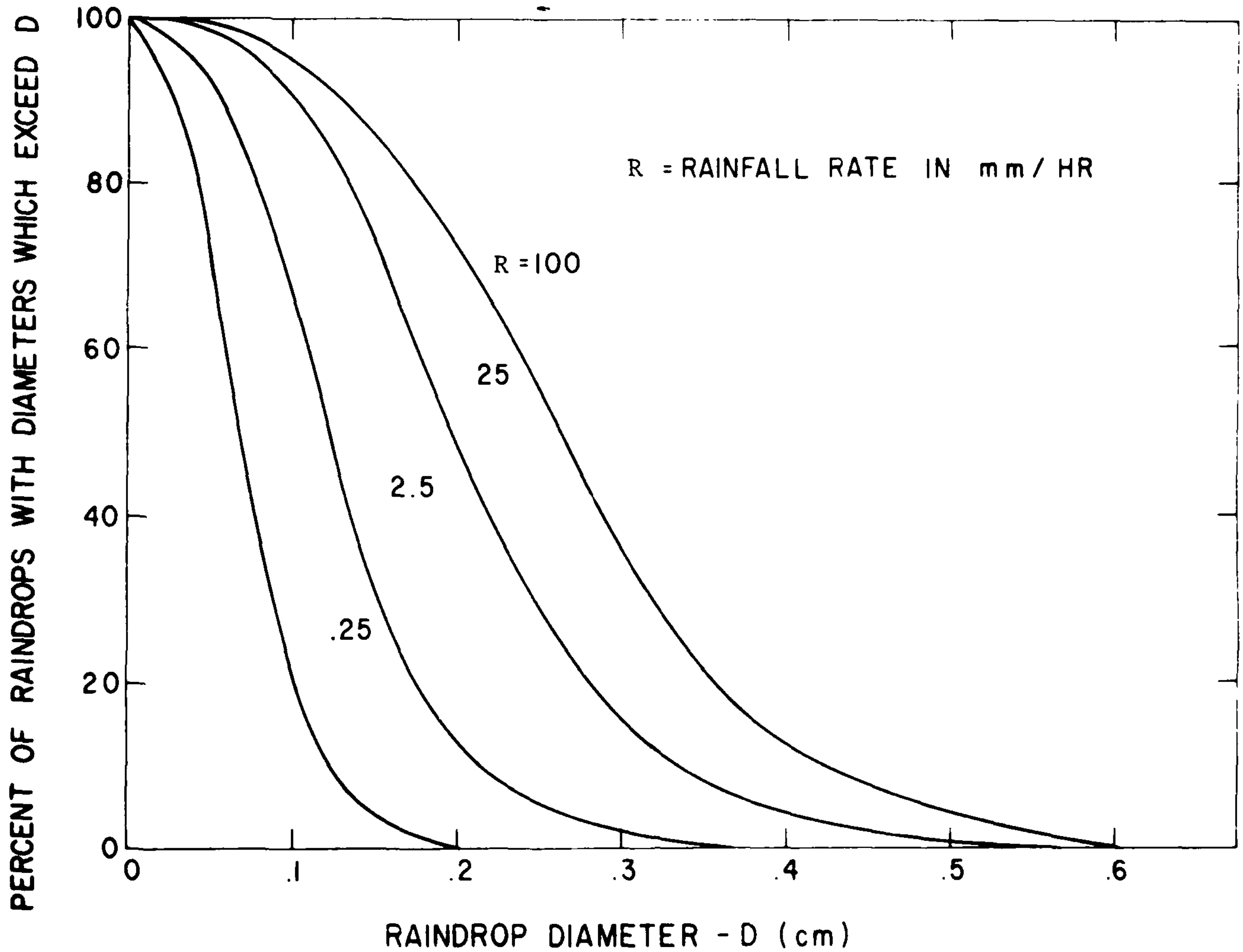

Figure 2. Distribution of Raindrop Size as a Function of Rain Rate

The attenuation can be expressed in the form

$$A = 0.4343 \int_0^\infty N(D) Q_t(D\Lambda) dD, \tag{1}$$

where N(D)dD is the number of drops per cubic meter having diameters in the range dD, Q_t is the total cross section of each drop, and the attenuation is measured in decibels per kilometer. Rain is often assumed to have an exponential distribution of drop diameters, so that

$$N(D) = N_0 e^{-\Lambda D}, \tag{2}$$

where N_0 and Λ are empirical constants that are a function of the type of rain and more particularly the rain rate. The original rain attenuation calculations were done by Ryde and Ryde[7]; these were later refined by Medhurst[1]. Attenuations based on Medhurst's calculations are plotted as a function of rain rate in Figure 3.

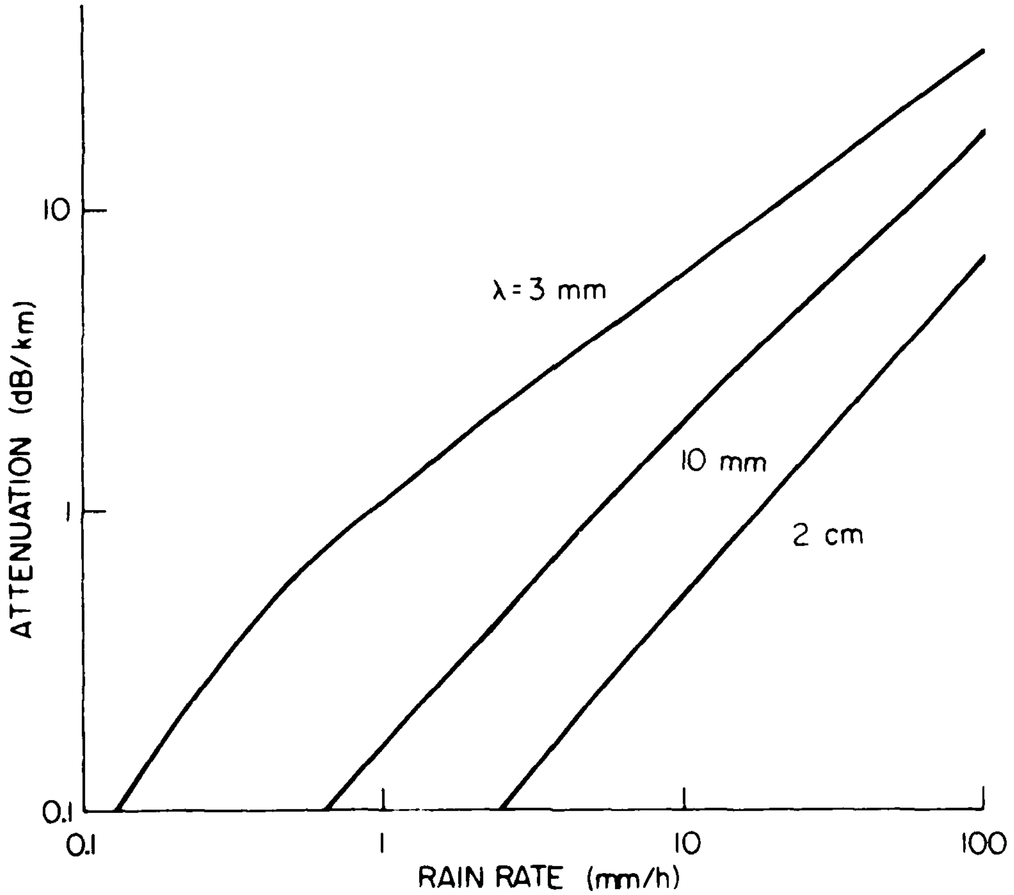

Figure 3. Rain Attenuation as a Function of Rain Rate

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7. Ryde, J.W. and Ryde, D. (1945) *Attenuation of Centimeter and Millimeter Waves by Rain, Hail, Fogs, and Clouds*, General Electric Company, Wembly England, Rep. 8670.

These curves can be approximated by the expression

$$A = aR^{b}, \tag{3}$$

where a and b are empirical constants that are a function of wavelength, type of rain, and temperature. R is the rain rate in millimeters per hour, and the attenuation is measured in decibels per kilometer. Olsen et al[8] calculated rain attenuation as a function of rain rate using the Mie formulation for a number of different drop size distributions and then performed a logarithmic regression to obtain values for a and b. These values have been tabulated for frequencies from 1 to 1000 GHz; although they are believed to provide a good approximation to the attenuation, it should be remembered that they are statistical and must be interpreted accordingly.

3. DESCRIPTION OF EXPERIMENT

The experiment was conducted at a frequency of 35 GHz over an 18.3-km path between Griffiss Air Force Base (GAFB) in Rome, NY and the town of Verona. This link is part of the Rome Air Development Center (RADC) EHF Experimental Communication Network that was set up to evaluate EHF communication equipment. A layout of the link is shown in Figure 4. The transmitting and receiving

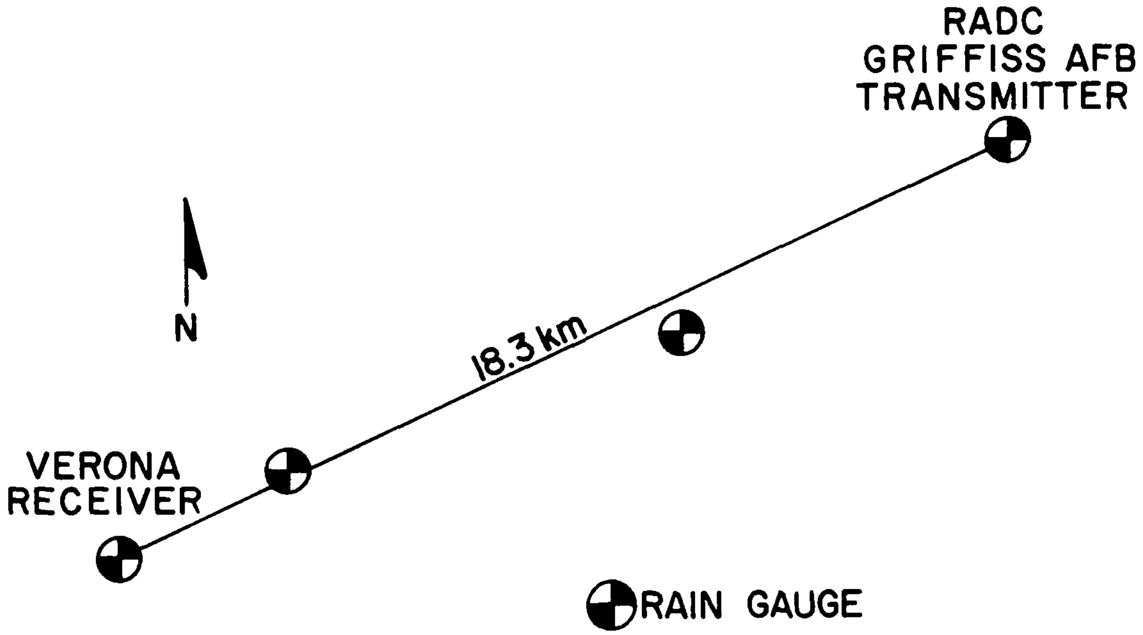

Figure 4. Path Geometry

8. Olsen, R.L., Rogers, D.V., and Hodge, D.B. (1978) The aR^{b} relation in the calculation of rain attenuation, *IEEE Trans. Antennas Propag.* **AP-13**(4), 550-564.

antennas were 53-cm lenses at heights of approximately 30 and 60 meters above the ground at the Griffiss AFB and Verona sites, respectively. The beamwidths of the antennas were sufficiently narrow and the antennas were sufficiently high above ground so as to preclude interference from any terrain effects. Each of the antennas was located in a shroud. This helped to shield the aperture from rain; however, if the rain direction had a horizontal component, some rain could collect on the lens surface, but this rolled off very quickly. There was a tipping-bucket rain gauge at each terminal and two other rain gauges along the path. One was located about 3.5 km from the transmitter at Verona; the other was about 7.1 km from GAFB. Received signal level and rain rate were recorded at 1-min intervals.

The system used to measure attenuation as a function of rain rate was not designed for propagation measurements; as a result, there were several limitations. The most serious was the limited dynamic range of the receiver; less than 30 dB of dynamic range was available for measuring the excess path attenuation due to rain. This translated to maximum excess attenuations of only about 1.6 dB/km which limited measurements to rain rates of less than 5 mm/hr. There was also a limitation due to the tipping-bucket rain gauges. These gauges tip at a level of 0.1 mm. Since a rate of 0.1 mm per minute corresponds to 6 mm per hour, this would be the minimum rain rate that could be used if the data were analyzed on a minute-by-minute basis. Since this experiment is limited to lower rain rates, the data were integrated over a 6-min period. In order to obtain an average rain rate for the path, the rain rates recorded by the four rain gauges were weighted equally and averaged. Consideration was given to utilize wind speed and direction data so as to obtain a more accurate average rain rate; it was later realized, however, that this procedure was too complicated. For a 6-min integration time, the minimum path-average rain rate was 0.25 mm/hr. This corresponded to a single tip by any one of the four rain gauges during the 6-min period.

Equipment malfunctions prevented data from being collected continuously. In addition, it was found that the rain gauges did not operate reliably during snow and very cold weather, so they were not used during the winter. Therefore, it was not possible to obtain percent time statistics for rain attenuation for upper New York State. However, even with these limitations, many hours of rain attenuation data were collected.

4. ANALYSIS OF DATA

From June through November 1985, 91.5 hours of rain attenuation data were obtained during the course of 10 rainstorms. An average received signal level in dB and a path-average rain rate in mm/hr were obtained for each 6-min period of rain. Since this experiment was limited to attenuations that corresponded to rain rates of less than 5 mm/hr, the Marshall-Palmer rain model was used; it is considered to be more applicable for widespread rain in continental temperate climates, such as upper New York State, than the Laws and Parsons model. From Olsen et al[8], for a nominal temperature of 20°C and for a frequency of 35 GHz

$$A(\mathrm{dB/km}) = .268R^{.999}. \tag{4}$$

For convenience this can be approximated by

$$A(\mathrm{dB/km}) = .268R \tag{5}$$

$$A(dB/18.3km) = 4.90R. \tag{6}$$

A linear regression for attenuation vs rain rate was performed for each set of data; it has the form

$$A(dB) = A_0 + A_1R \tag{7}$$

The constant term A_0 of the regression line corresponds to a relative attenuation that exists if there is no rain present. The coefficient A_1 of the rain rate R is for an 18.3-km path.

One of the best sets of data is for the rainfall of 19 October 1985 and is shown in Figure 5. It rained

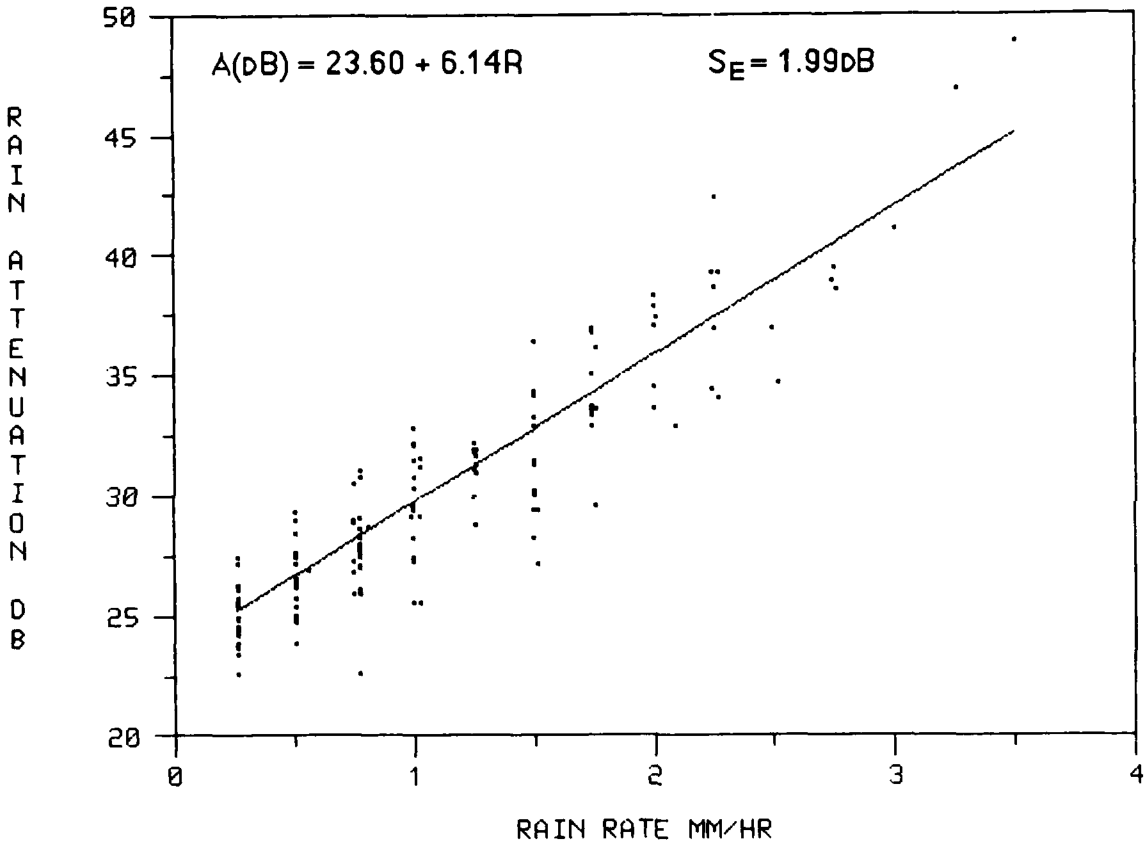

Figure 5. Scatter Plot of Rain Attenuation vs. Rain Rate - 19 October 1985

almost continually for a period of about 15 hours; 14 hours of data were recorded during that time. Path-average rain rates ranging from a minimum value of 0.25 mm/hr to a maximum value of 3.5 mm/hr were measured. The regression line for this set of data for the 18.3-km path is

$$A(dB) = 23.6 + 6.14R \tag{8}$$

The standard error of the estimate is 1.99 dB; this translates into only slightly more than 0.1 dB/km. The correlation coefficient for the data is 0.91 which is relatively high considering the variability of rain. The coefficient of R is about 20 percent higher than would have been predicted from Olsen et al[8].

Of the remaining data, the respective regression lines had slopes and standard errors that were comparable to the data of 19 October 1985 with the exception of the rain that occurred on 24 September and 13 October. These data produced regression lines with slopes that were significantly lower than the others and had standard errors that were significantly higher. There is no apparent explanation for this difference. The statistics for all the rain data are summarized in Table 1. Plots of attenuation vs. rain rate for the remaining days are given in the Appendix.

Table 1. Summary of Rain Attenuation Statistics

DATE (1985)	TIME START	TIME END	N SAMPLE SIZE	A_0	A_1	S_E
6/12	0512	1330	70	23.37	6.13	3.98
7/31	1054	1948	69	24.29	6.83	4.04
9/24	1206	1836	42	24.65	4.56	4.56
10/1-2	2124	0900	101	21.44	6.16	1.96
10/13	0048	1512	76	24.61	4.55	4.34
10/19	0142	1636	140	23.60	6.14	1.99
10/24	1536	1848	33	25.02	6.48	2.57
11/5	0500	1618	82	22.33	7.37	2.25
11/9-11	0018	1024	242	21.85	7.56	1.83
11/13-14	1024	0100	60	21.95	7.18	1.79

$A\,(\mathrm{dB}) = A_0 + A_1 R$
A_0 = Reference attenuation for no rain (dB)
A_1 = Coefficient of rain rate
R = rain rate in MM/Hr
S_E = standard error of estimate
N = number of 6-min intervals

5. CONCLUSION

An attempt has been made to conduct a controlled experiment on attenuation as a function of rain rate. Initially, it was assumed that if light rain tends to be somewhat uniform and widespread, then four rain gauges may be sufficient for estimating a path-average rain rate for the 18.3 km path. Based on the results that have been obtained, it appears that this assumption may have led to higher rain rates than would have been predicted by theory. Eight sets of rain data produced regression lines having slopes that ranged from about 6 to 7.5. Seven of these sets of data had standard errors that were less than about 2.5. Two sets of data produced statistics that showed much more variability.

A weighted average for the slope of the regression line is 6.55. This is about 33 percent higher than the value of 4.90 from Olsen et al[8].

In summary, it appears that the results obtained from this experiment indicate that rain attenuation has a fair amount of variability with respect to the rain rate even for widespread light rain. The average attenuation is higher than that predicted by theory; however, there is a logical explanation for this result. Since the rain gauges were sparsely spread along the path and since heavy rain tends to be quite localized, it is very possible that heavy rain actually occurred along the path but went undetected. The availability of more rain gauges along the path would have helped to reduce the possibility of this outcome. Since more controlled experiments over shorter paths have produced results that agree with theory, it is our opinion that previous experiments, over long paths, that produced higher attenuations than expected may have been subject to some of the same problems that we encountered.

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1. Medhurst, R.G. (1965) Rainfall attenuation of centimeter waves: comparison of theory and experiment, *IEEE Trans. Antennas Propag.* **AP-26**(2), 318-329.
2. Norbury, J.R. and White W.J.K. (1972) Microwave attenuation at 35.8 GHz due to rainfall, *Electron. Lett.* **8**, 91-91.
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4. Zavody, A.M. and Harden, B.N. (1976) Attenuation/rain-rate relationship at 36 and 110 GHz, *Electron. Lett.* **12**, 422-424.
5. Mink, J.W. (1973) Rain-attenuation measurements of millimeter waves over short paths, *Electron. Lett.* **9**, 198-199.
6. Burrows, C.R. and Atwood, S.S. (1949) *Radio Wave Propagation*, New York: Academic Press, 1949.
7. Ryde, J.W. and Ryde, D. (1945) *Attenuation of Centimeter and Millimeter Waves by Rain, Hail, Fogs, and Clouds*, General Electric Company, Wembly England, Rep. 8670.
8. Olsen, R.L., Rogers, D.V., and Hodge, D.B. (1978) The aR^b relation in the calculation of rain attenuation, *IEEE Trans. Antennas Propag.* **AP-13**(4), 550-564.

Appendix

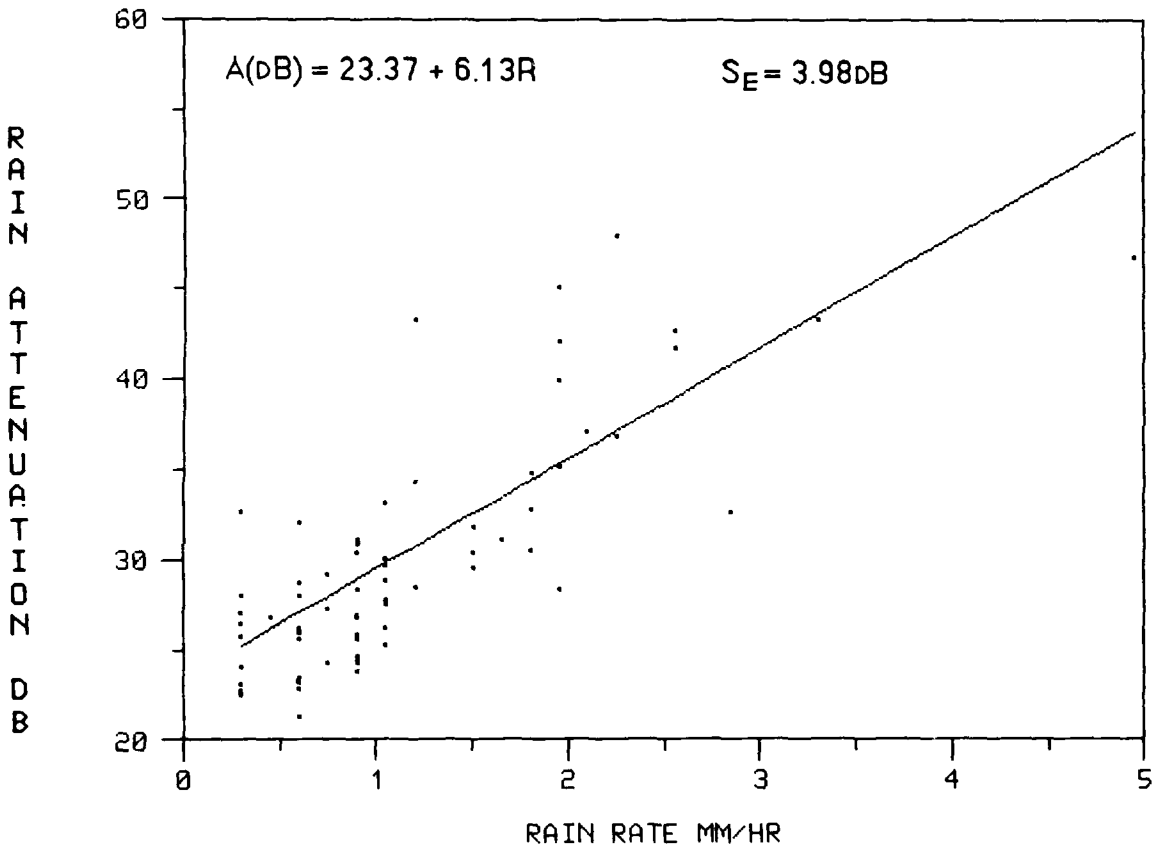

Figure A.1. Scatter Plot of Rain Attenuation vs. Rain Rate - 12 June 1985

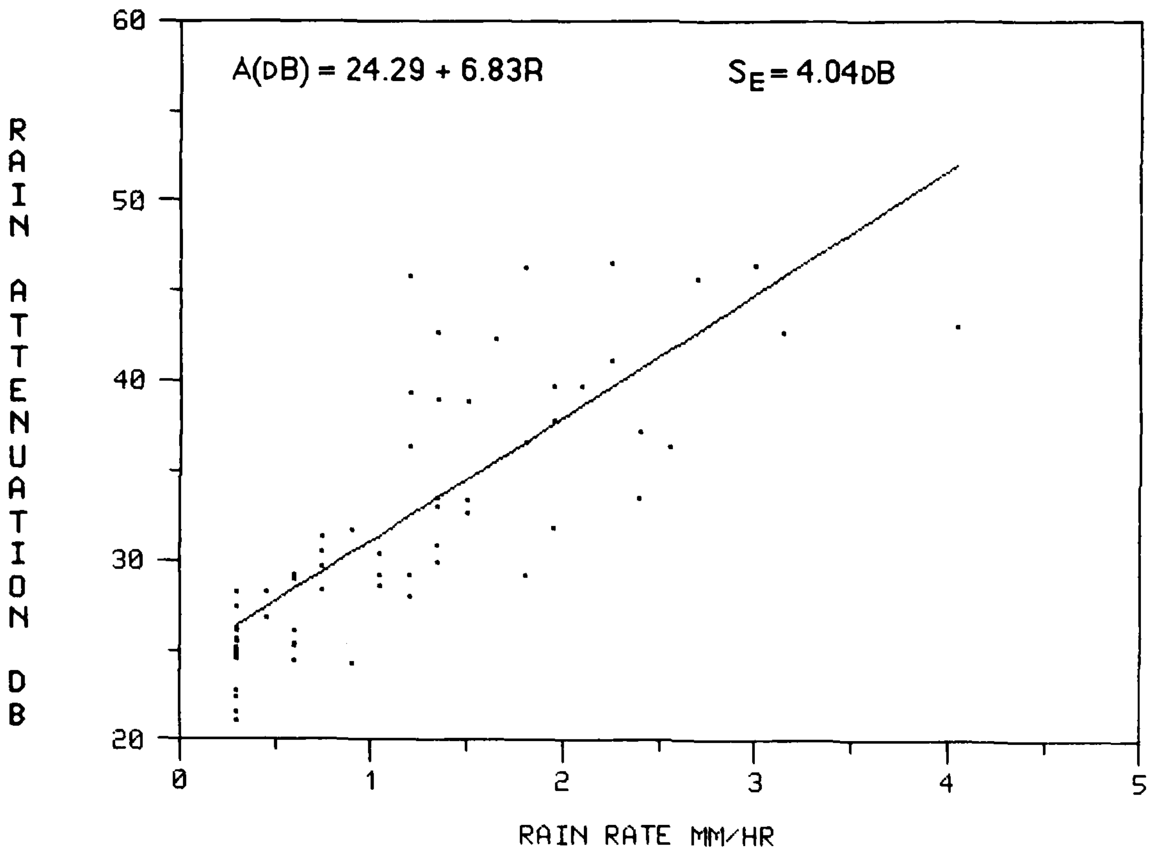

Figure A.2. Scatter Plot of Rain Attenuation vs. Rain Rate - 31 July 1985

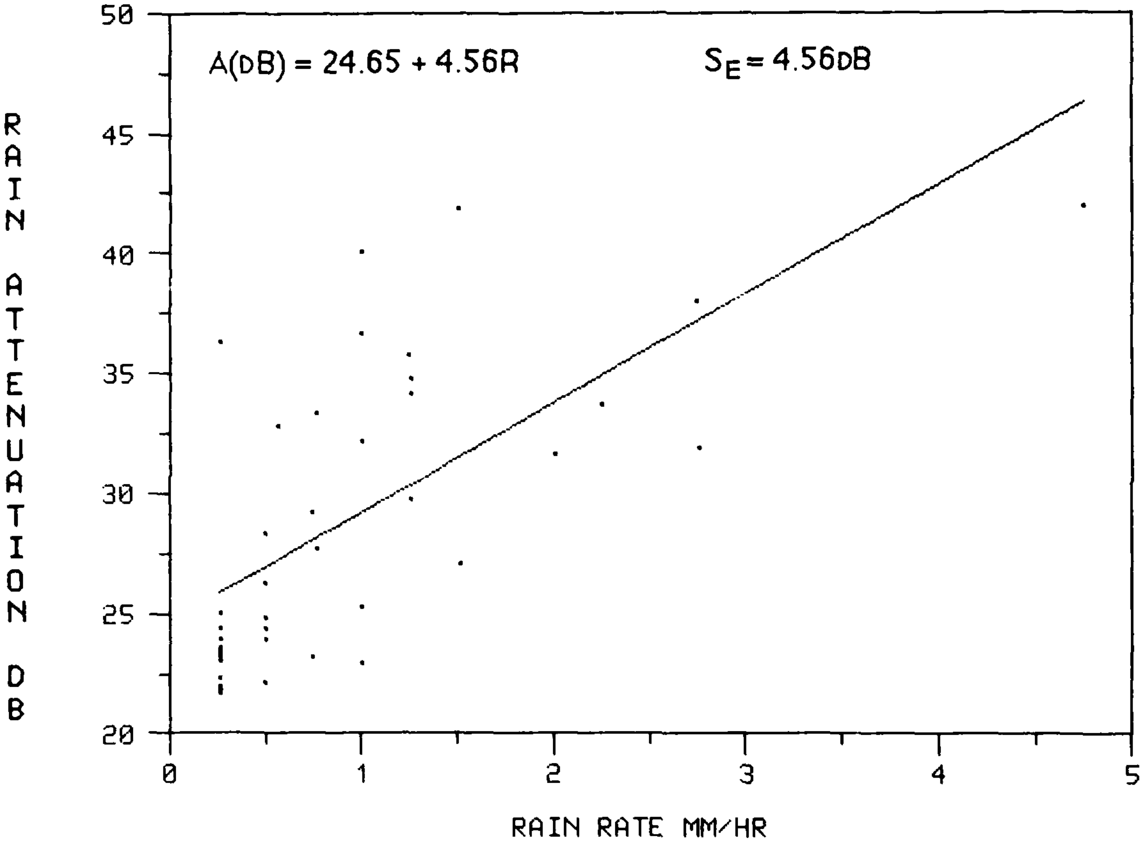

Figure A.3. Scatter Plot of Rain Attenuation vs. Rain Rate - 24 September 1985

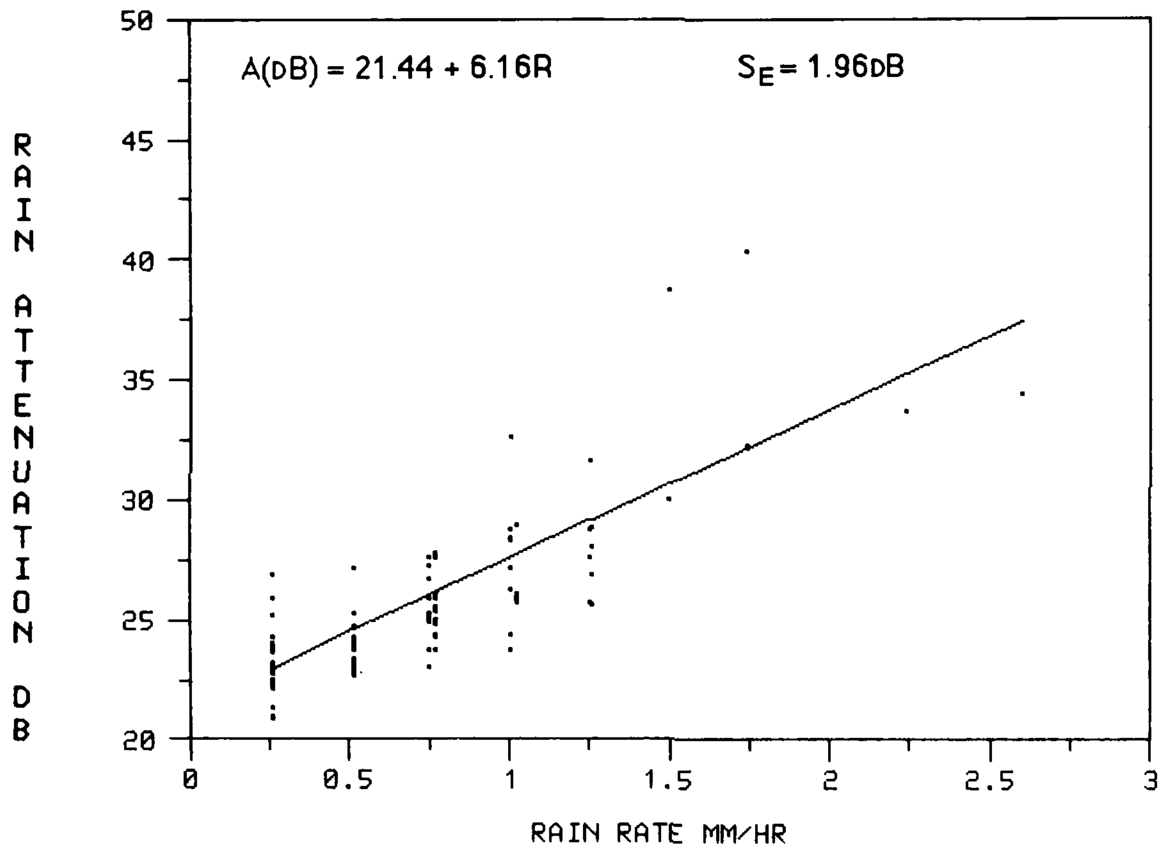

Figure A.4. Scatter Plot of Rain Attenuation vs. Rain Rate - 1-2 October1985

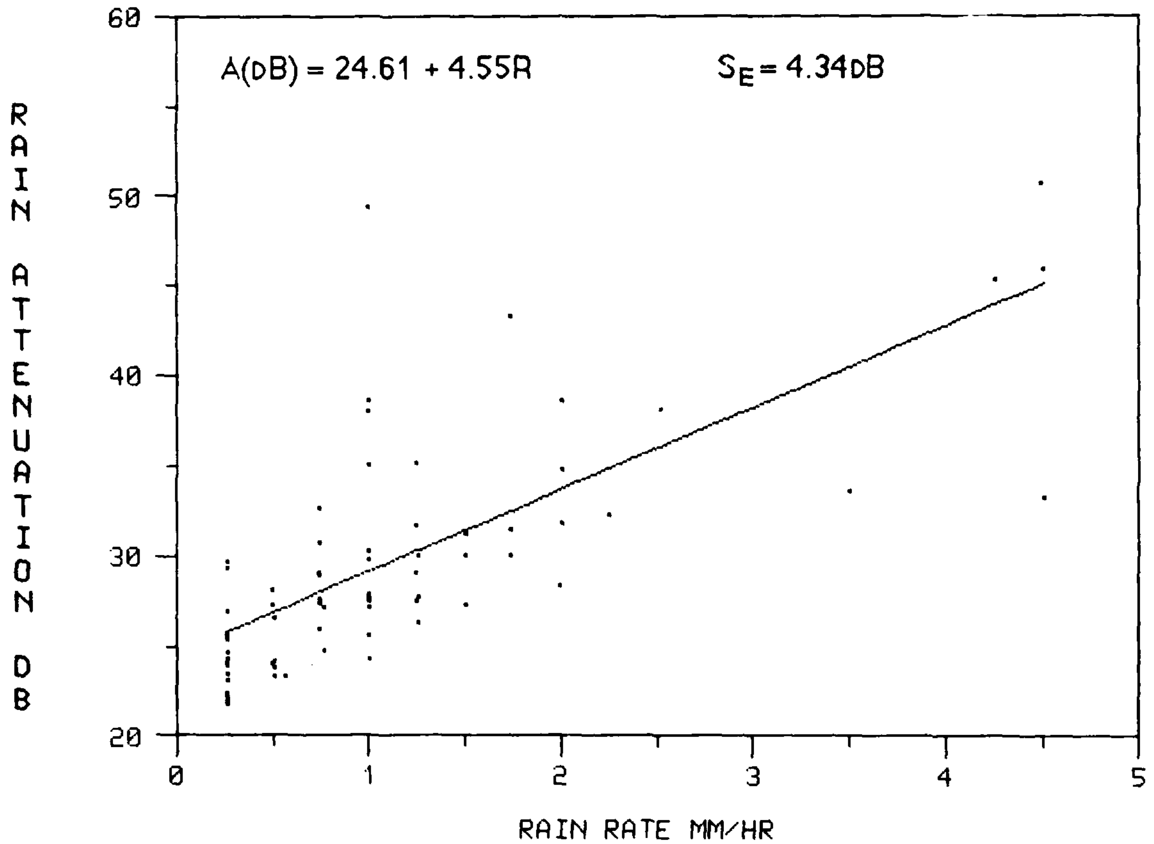

Figure A.5. Scatter Plot of Rain Attenuation vs. Rain Rate - 13 October 1985

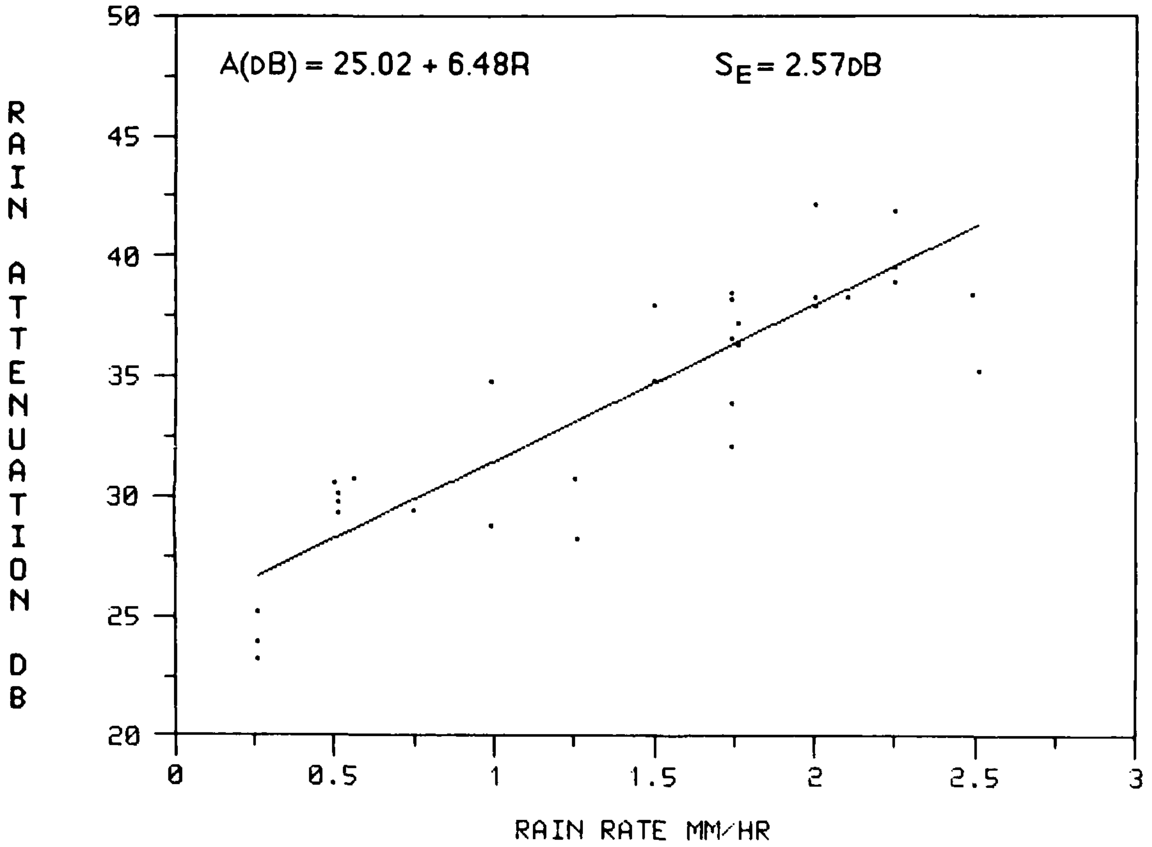

Figure A.6. Scatter Plot of Rain Attenuation vs. Rain Rate - 24 October 1985

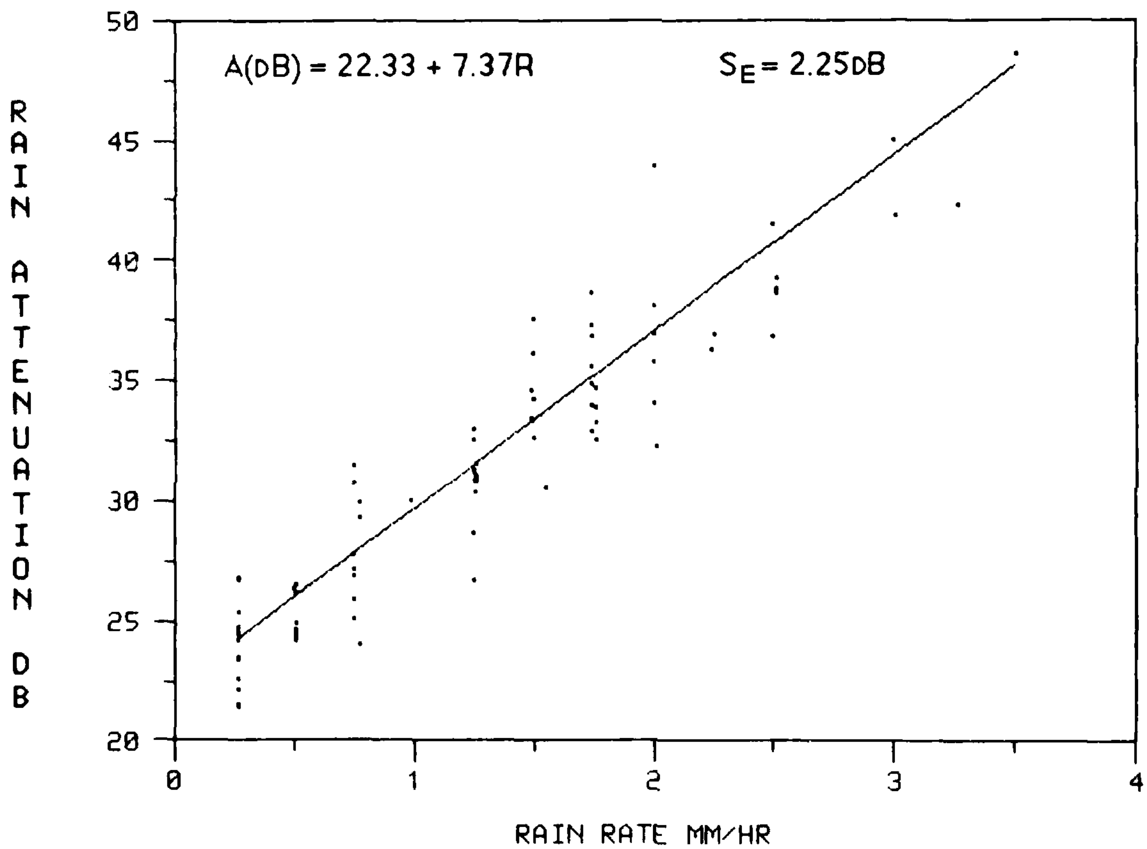

Figure A.7. Scatter Plot of Rain Attenuation vs. Rain Rate - 5 November 1985

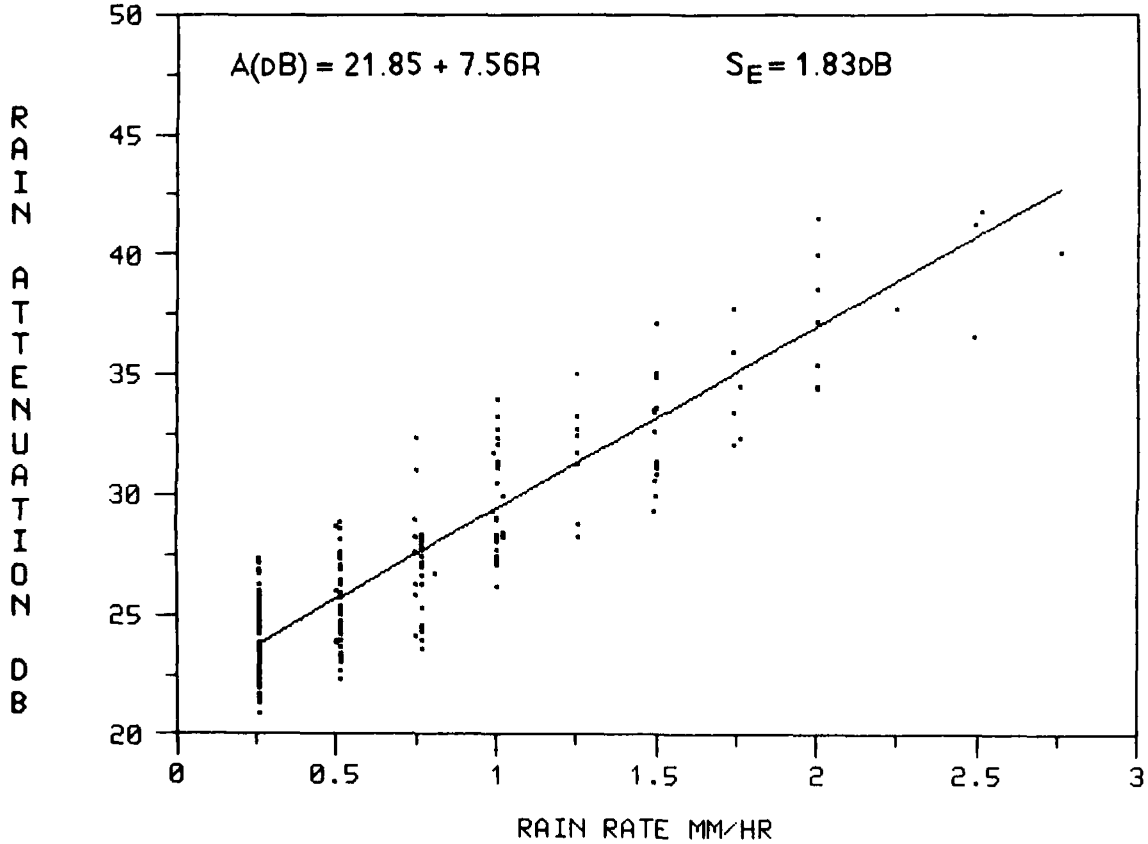

Figure A.8. Scatter Plot of Rain Attenuation vs. Rain Rate - 9-11 November 1985

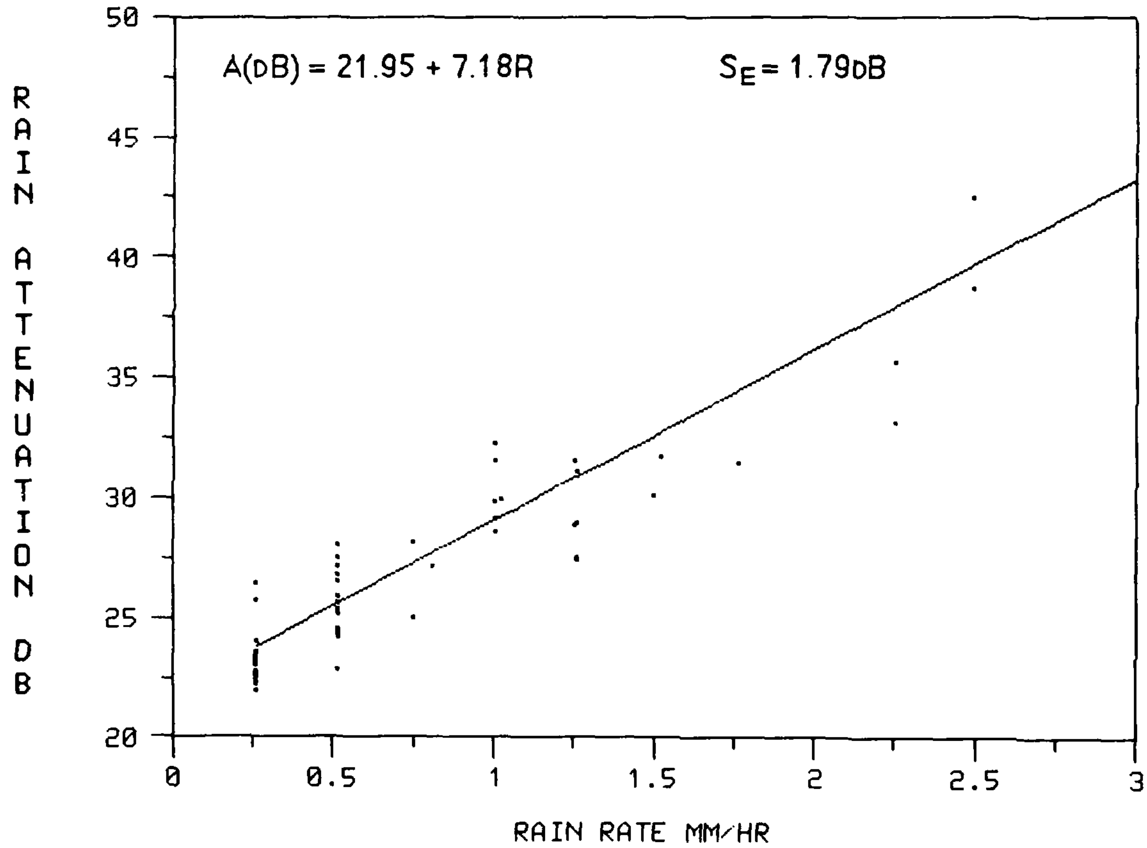

Figure A.9. Scatter Plot of Rain Attenuation vs. Rain Rate - 13-14 November 1985

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